EUV Lithography

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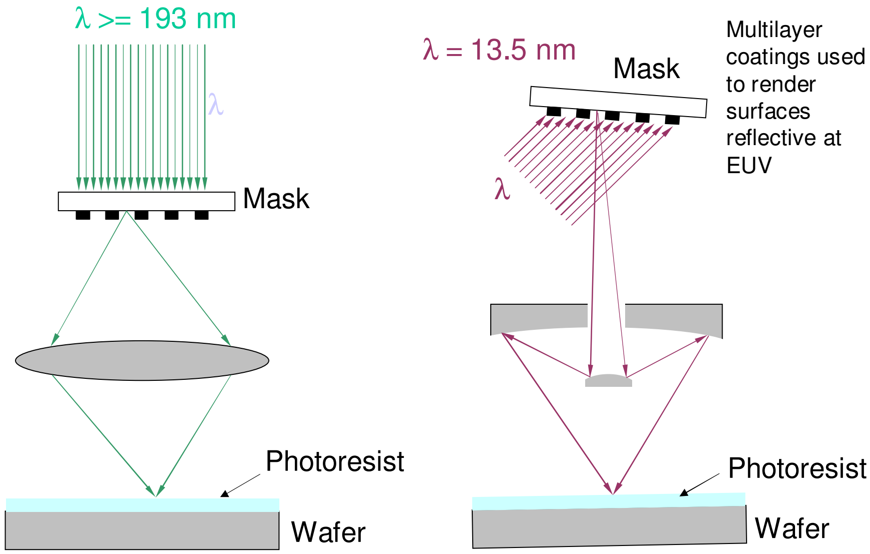
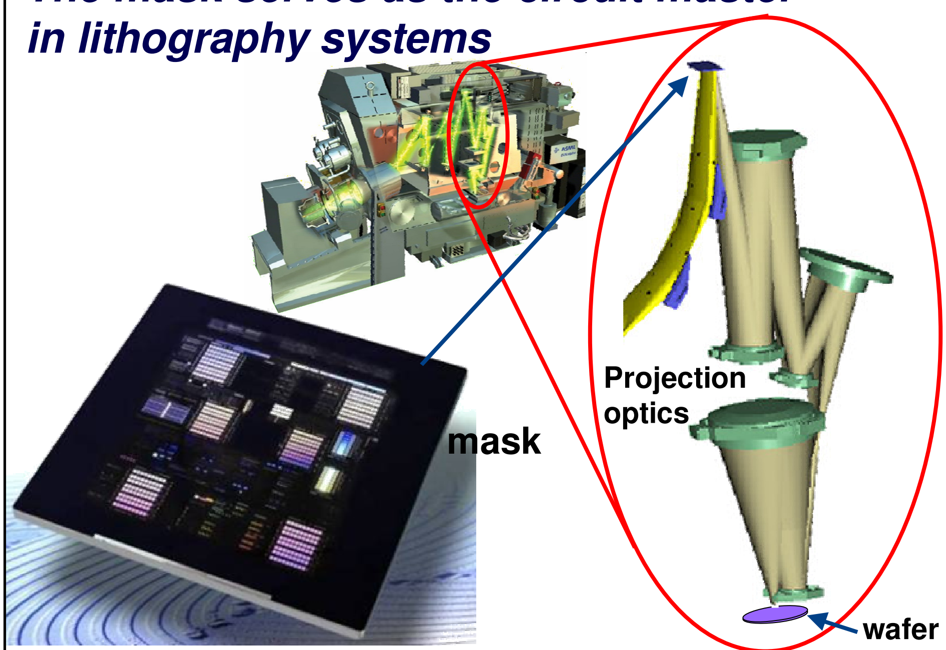
Outline

- Introduction
- Review of key optics concepts for lithography
- EUV Capabilities/Challenges
- EUV patterning and resists
- Mask defects and printing

EUV: extension of optical lithography



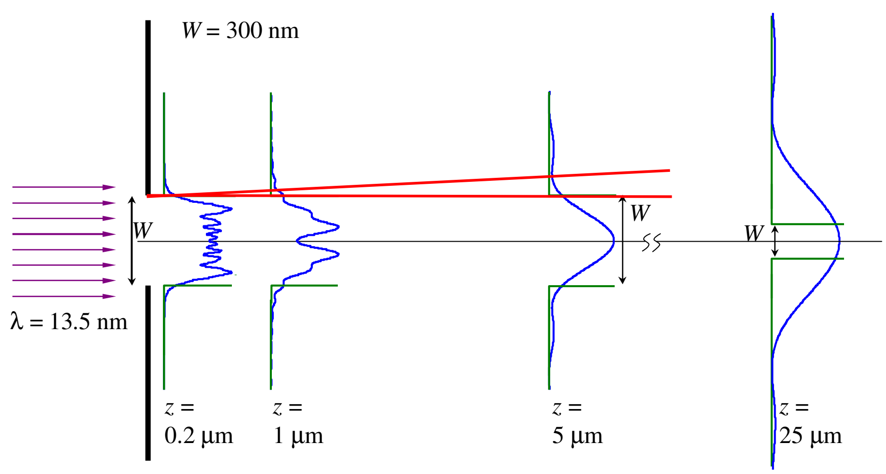
The mask serves as the circuit master in lithography systems



Review of key optics concepts for lithography

- Diffraction
  - Resolution
  - Depth of focus
- Partial coherence
- Etendue

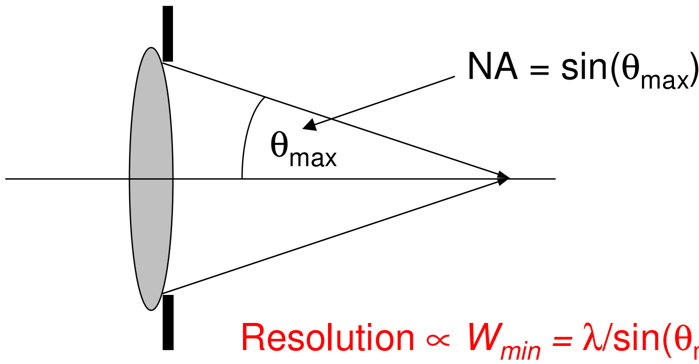
Diffraction



Angular spread, $\theta = \mathrm{asin}(\lambda/W)$

Image formation: inverse diffraction

- Function of lens is to invert diffraction process
  - $\theta = \mathrm{asin}(\lambda/W) \Rightarrow W_{min} = \lambda/\sin(\theta_{max})$

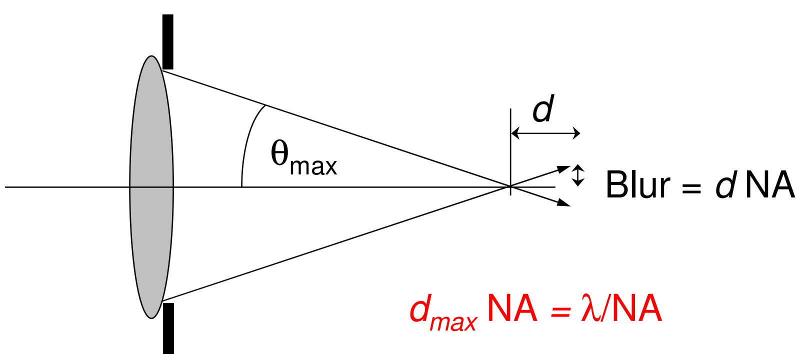


Resolution $\propto W_{min} = \lambda/\sin(\theta_{max}) = \lambda/\mathrm{NA}$

Res = $k_1\ \lambda/\mathrm{NA}$

Depth of focus

- Let DOF be proportional to distance where single-sided blur = resolution



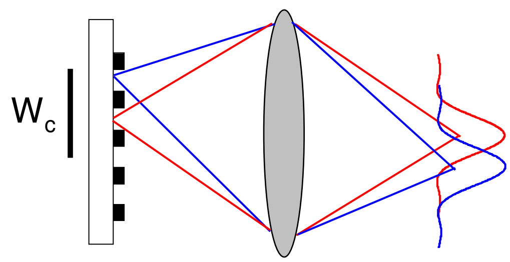
$d_{max}\ \mathrm{NA} = \lambda/\mathrm{NA}$

DOF $\propto d_{max} = \lambda/\mathrm{NA}^2$

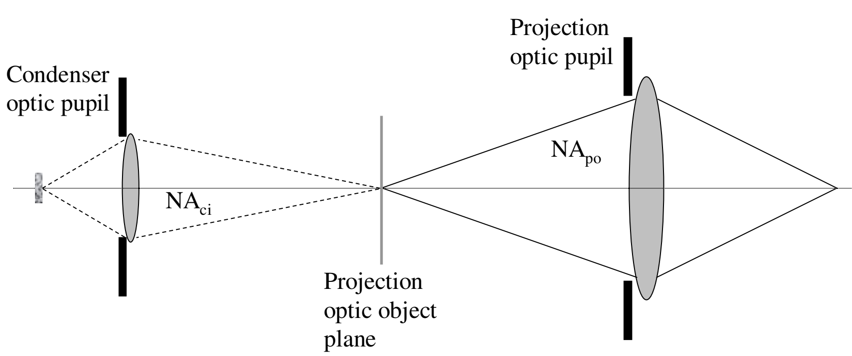
DOF = $k_2\ \lambda/\mathrm{NA}^2$

Concept of partial coherence factor (σ)

- Most fundamentally, σ is the ratio of mask-side resolution limit to coherence width (W_c)
- Large W_c = small σ
- Determines area over which object components add coherently



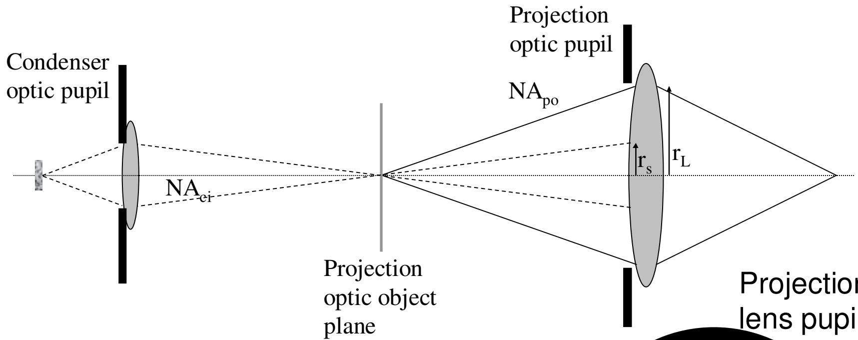
Critical illumination: σ = ratio of NAs

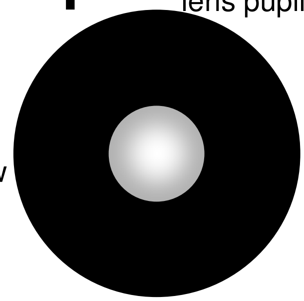


$W_c \propto 1/NA_{ci}$ $\quad$ $Res_o \propto 1/NA_{po}$

$$\sigma = Res_o/W_c = NA_{ci}/NA_{po}$$

Pupil fill: alternative view of σ

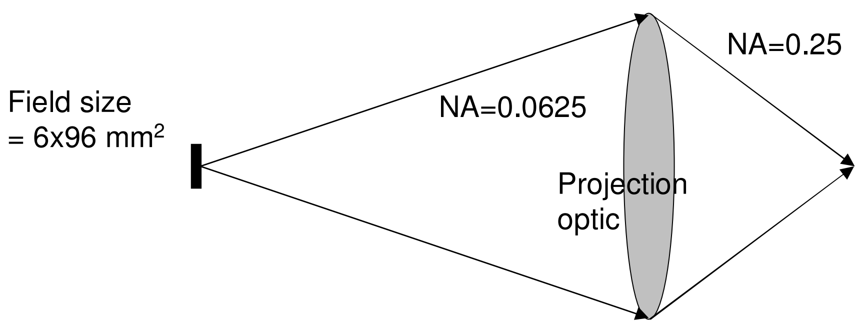




$\sigma = NA_{ci}/NA_{po} = r_s/r_L$

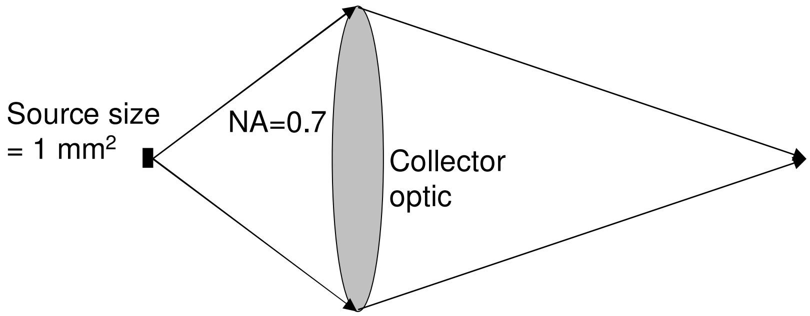
Example view of pupil fill for $\sigma = 0.35$

Etendue: space-bandwidth product



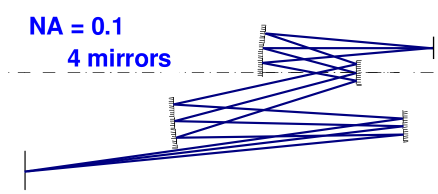
- The optic etendue (maximum accepted space-bandwidth product) is
  - Field of view area X acceptance solid angle
  - $6*96*0.01\ mm^2\ sr \sim 7\ mm^2\ sr$

Projection optics etendue limits usable source etendue and thus power

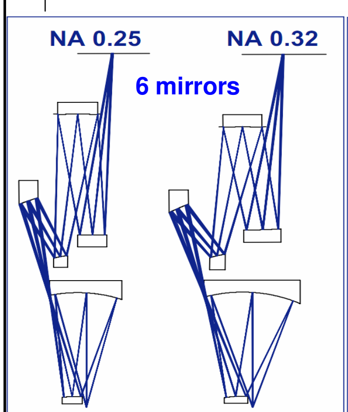


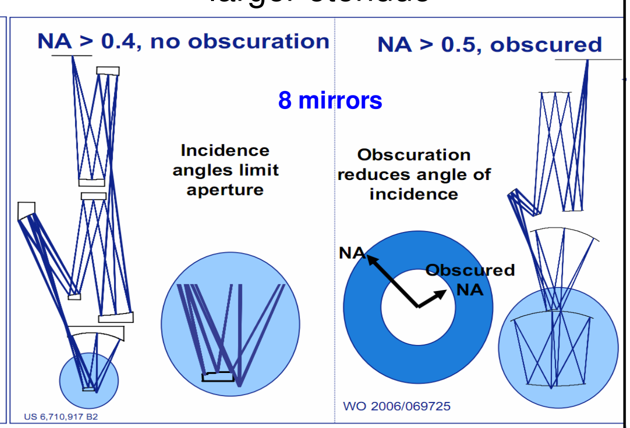
- A 1 mm source with 45-degree collection would have an etendue of ~2 mm^2 sr (min σ = 0.53)
- A 0.1 mm source with 70-degree collection would have an etendue of ~0.04 mm^2 sr (min σ = 0.08)

Increasing NA demands more mirrors



- More mirrors means lower throughput
- But, larger NA means larger etendue

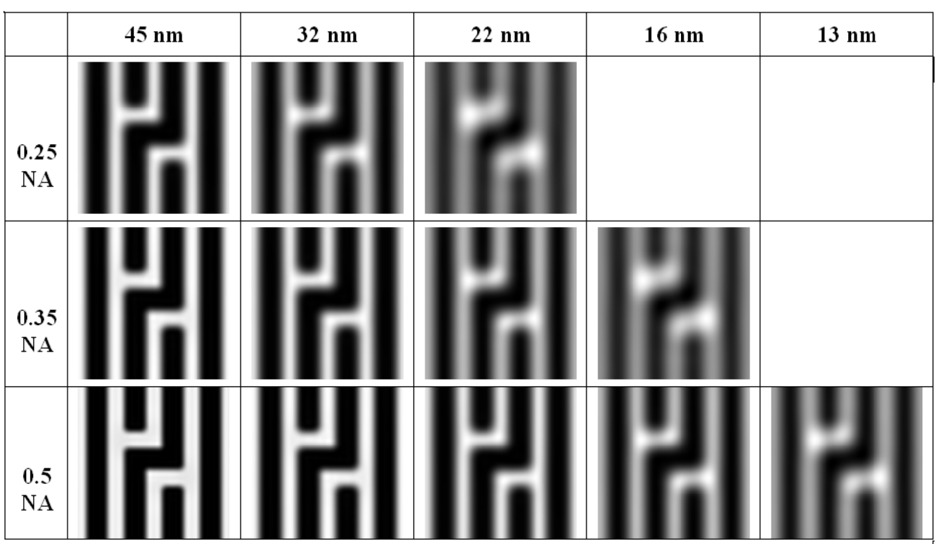




EUV Patterning Capabilities:
modeling

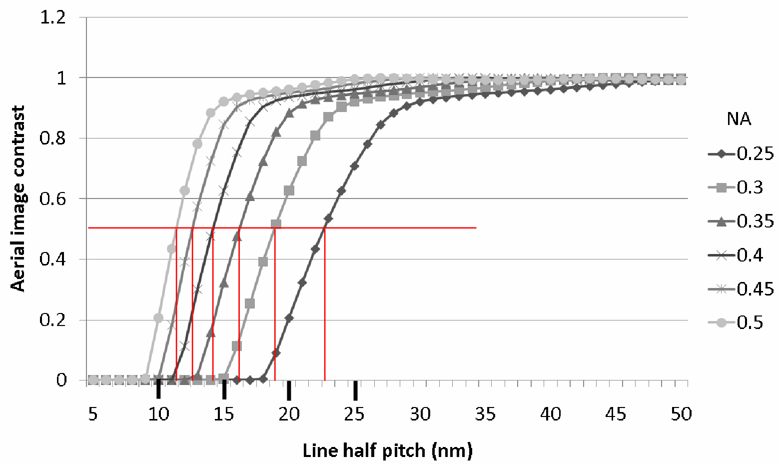
Extendibility of EUV

Binary amplitude mask, σ = 0.7, no OPC, no bias correction



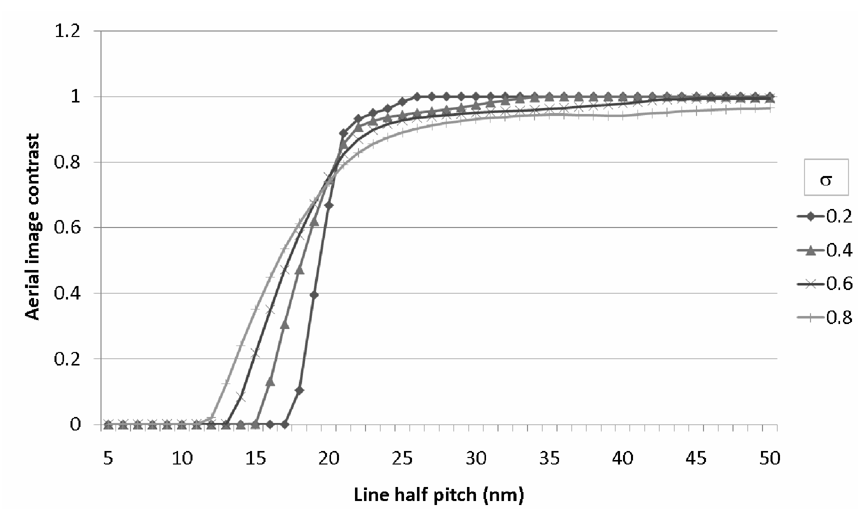
Optical transfer function vs NA

Binary amplitude mask, σ = 0.5, no aberrations



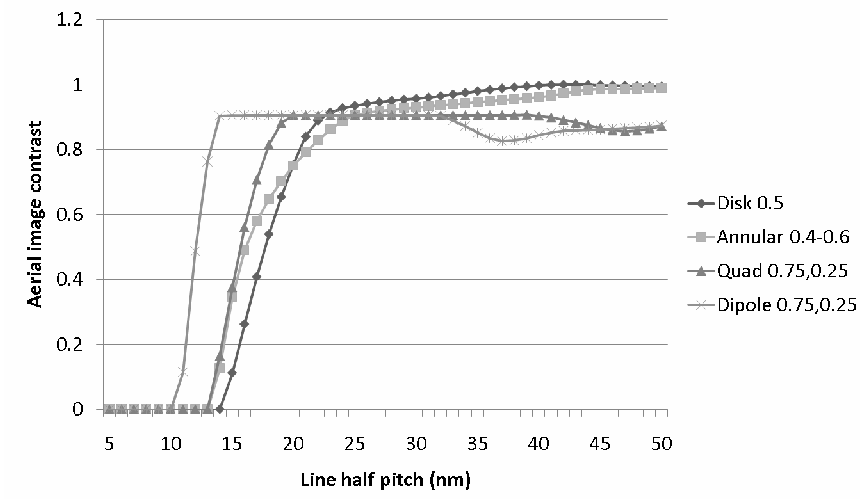
Optical transfer function through sigma

Binary amplitude mask, NA = 0.32, no aberrations



Optical transfer function through illumination type

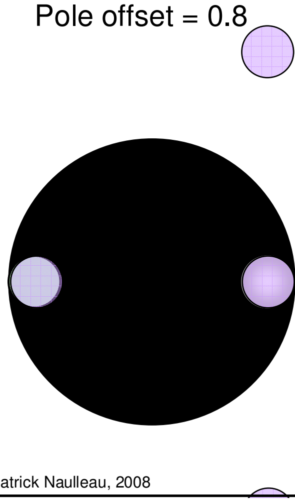
Binary amplitude mask, NA = 0.32, no aberrations

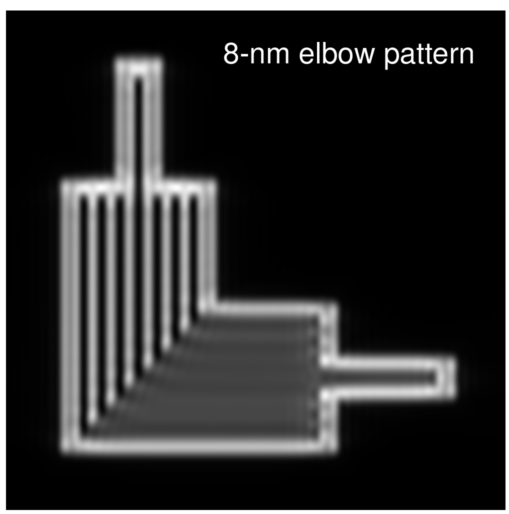


8-nm possible at 0.5 NA with conventional mask

Binary amplitude mask, dipole illumination, no OPC, no bias correction

Pole radius = 0.2
Pole offset = 0.8





EUV-specific challenges

Challenge	Consequence
EUV radiation is not transmitted through the atmosphere	Tool must operate in vacuum environment
All solid materials strongly absorb EUV radiation	Refractive optics not possible. Use only reflective mirrors & reticles
Hydrocarbons & water vapour are cracked by EUV, contaminating mirror surfaces – C deposition & oxidation of coatings	Minimize hydrocarbons and water vapour content in the tool. Needs cleanliness of ultra high vacuum (UHV)
Source chamber cannot be physically separated from imaging optics chamber	Contain any debris produced by source – particles & ions
EUV sources are inefficient producers of radiation	Efficient thermal management of waste heat from high input powers required
Vacuum clamping cannot be used. Air-bearing motion mechanisms are complex	Use electrostatic clamping, mag. Lev. stages
Tilted mask plane: system not telecentric at reticle	Strict reticle flatness requirements
Tilted mask plane: shadowing by 3D mask structure	Position dependent mask bias correction required
Short wavelength -> high scatter -> large position dependent flare	Long-range "proximity" correction required
Reflective mask leads to potential "buried" phase defects (< 3-nm tall)	Extremely high sensitivity mask blank inspection required

EUVL critical issue list

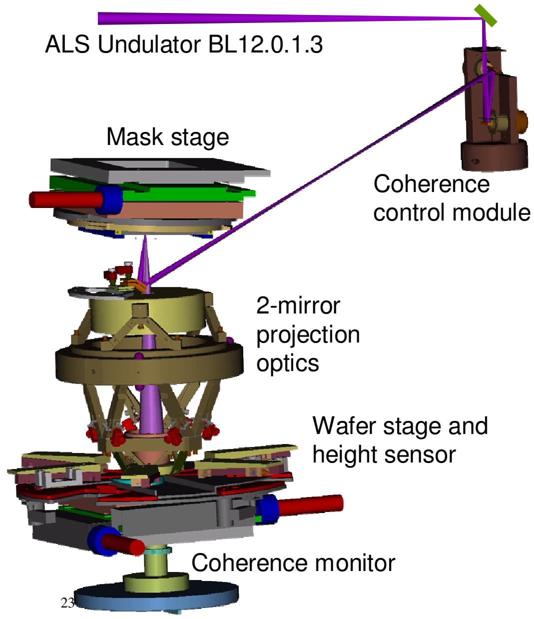
Top 3 Critical Issues

1. Reliable high-power source and collector module
    - Largely industrial effort
2. Availability of defect-free masks and mask infrastructure
3. Resist resolution, sensitivity & Line Edge Roughness (LER) met simultaneously

Ref: 2008 International EUVL Steering Committee

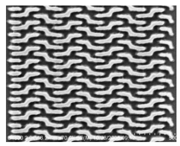
Berkeley EUV Nano-patterning tool designed to support advanced EUV research

- **Numerical aperture = 0.3**
- **Spatial resolution = 12 nm***
- **Supports approximately 200 user shifts per year with nearly 100% uptime**
- **Unique programmable coherence illuminator enables world's finest projection EUV resolution**
- **Supports:**
  - **Resist development**
  - **Mask development**
  - **Mask defect studies**



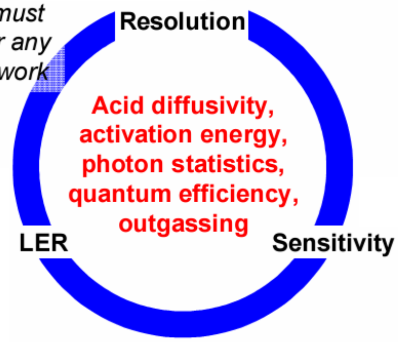
Worldwide user base including industry, academia, and research institutes

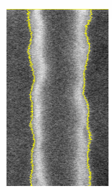
Simultaneously meeting resolution, sensitivity, and LER crucial issue for EUV resists



32-nm half pitch (21-nm iso) - 2013*
22-nm half pitch (15-nm iso) -2016
16-nm half pitch (11-nm iso) -2019

All three requirements must be met and balanced for any technology or it will not work





1.2 nm
0.8 nm
0.6 nm

10 mJ/cm^2
10 mJ/cm2
10 mJ/cm^2

LER: Line Edge Roughness

* 2007 ITRS Roadmap

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Although most EUV resists are based on 193 or 248 nm systems, EUV interaction with resist these materials is fundamentally different

- EUV energy (92 eV) many times higher than Photo Acid Generator (PAG) activation energy
- EUV interacts with all atoms, cannot be made to preferentially interact with PAG
- Photons do not directly activate PAG but rather generate secondary electrons upon interaction with first encountered atom
  - –Secondary electrons eventually activate PAG

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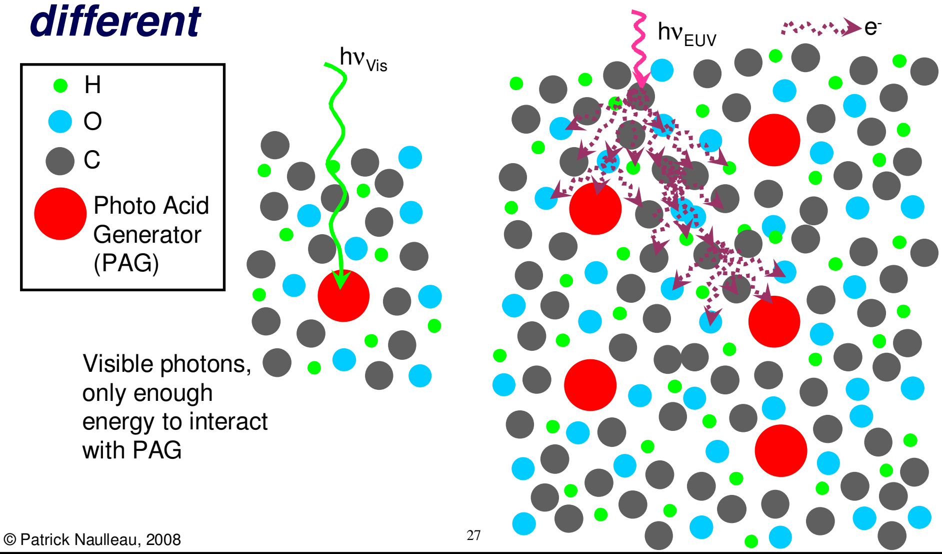
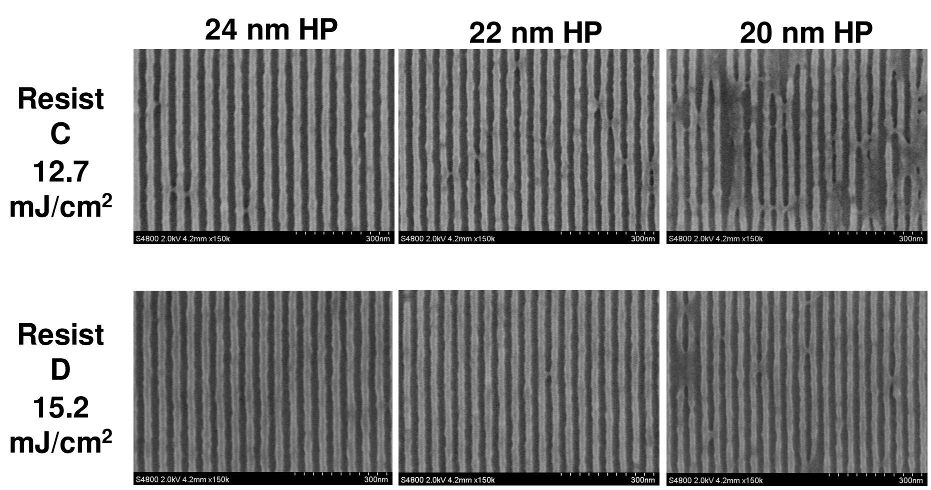
Although most EUV resists are based on 193 or 248 nm systems, EUV interaction with resist these materials is fundamentally different



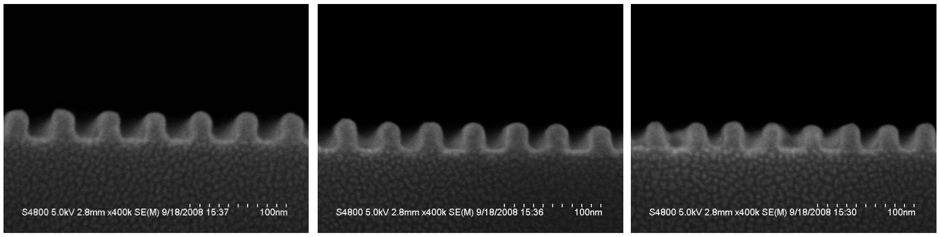
Chemically amplified resists now approaching 20 nm



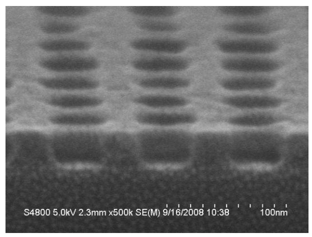
50-nm resist thickness

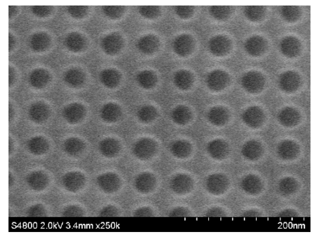
High pattern fidelity at small feature sizes

24 nm HP | 22 nm HP | 20 nm HP



30 nm 1:1 contacts



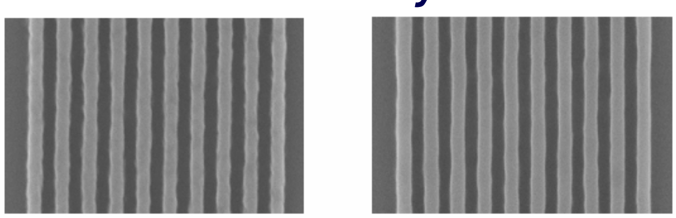


Resist D, film thickness = 50 nm

Rinse agents for LER reduction without resolution or sensitivity trade-offs

Berkeley MET

XP5494-C resist, Y-Monopole



Baseline Process	**Rinse Agent Process**
CD = 41.7 +/- 0.8 nm LER = 4.3 +/- 0.4 nm	CD = 40.6 +/- 0.6 nm LER = 3.2 +/- 0.4 nm

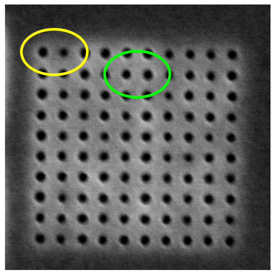
- Rinse agent applied instead of water after development
- ~1-nm reduction in LER observed
- No effect on resolution or sensitivity

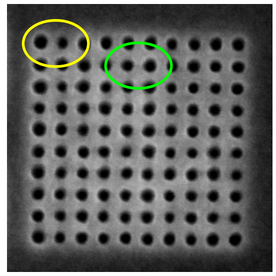
Data courtesy of Tom Wallow, AMD

Repeated printing of 35 nm contacts shows variation NOT dominated by photon noise

Esize | +15%

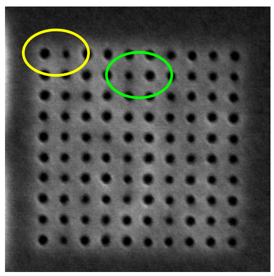
focus





RHEM Resist
Berkeley MET
Annular
E_0 = 10mJ/cm^2

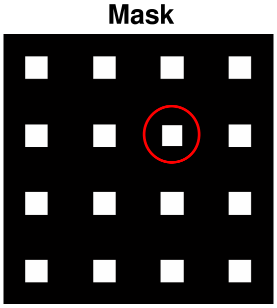
+50 nm



- 35-nm 1:2 contacts
- RMS size variation = 3.2 nm
- Reproducible size variation through dose and focus
- Contact variation must be dominated by mask

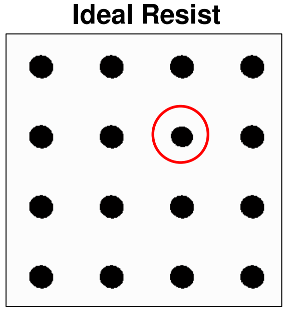
Optical mask error enhancement factor (MEEF) does not explain observed contact variation

Mask



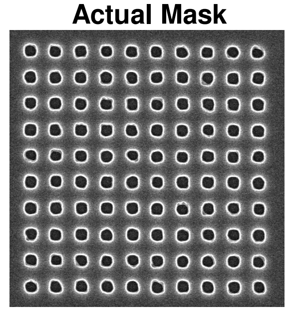
2.8 nm error on
35 nm contacts
(wafer coordinates)
Aerial-image
modeling includes
full EUV wavefront

Ideal Resist



MEEF = 1

Actual Mask

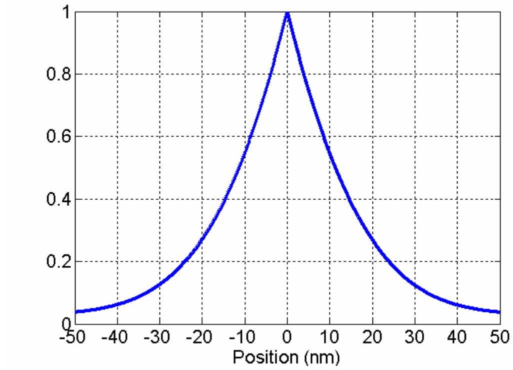


- 35 nm 1:1 contacts on 5x EUV mask
- RMS 1x diameter variation = 1.1 nm
- Resist var. = 1.1 nm

Modeling Resist Using Simple Point-Spread-Function (PSF) Method

- PSF resist modeling* is fast and convenient
- Model easily generated
- Provides intuitive link to resist resolution limit
- Few parameters makes model less susceptible to extrapolation errors
- Resist process well approximated by deprotection function**

"Deprotection blur" function PSF

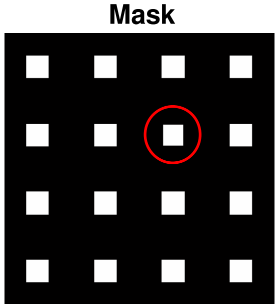


* C. Ahn, H. Kim, K. Baik, "A novel approximate model for resist process," Proc. SPIE **3334**, (1998).

** Gregg Gallatin, "Resist Blur and Line Edge Roughness," Proc. SPIE 5754, (2005)

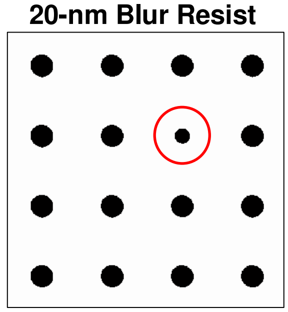
Resist blur dominates MEEF

Mask



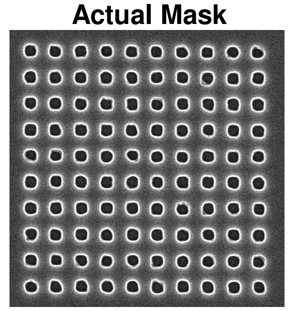
2.8 nm error on 35 nm contacts (wafer coordinates)
Aerial-image modeling includes full EUV wavefront

20-nm Blur Resist



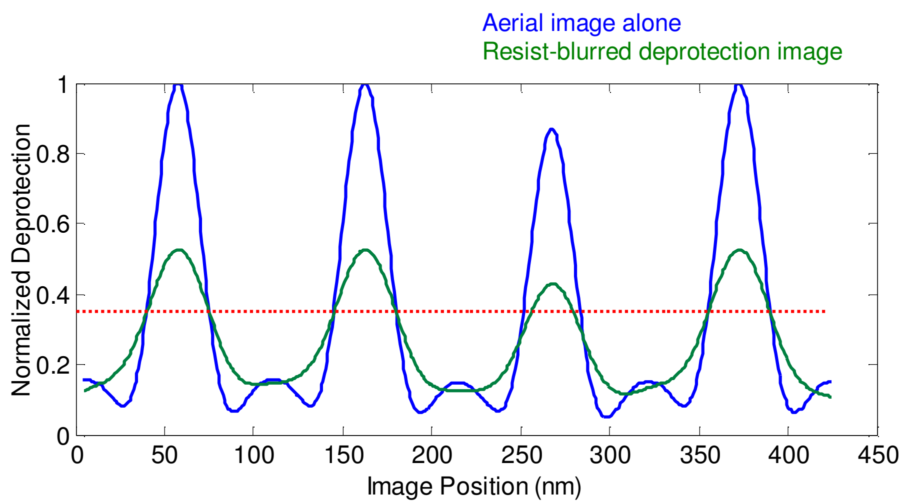
MEEF = 3.6

Actual Mask

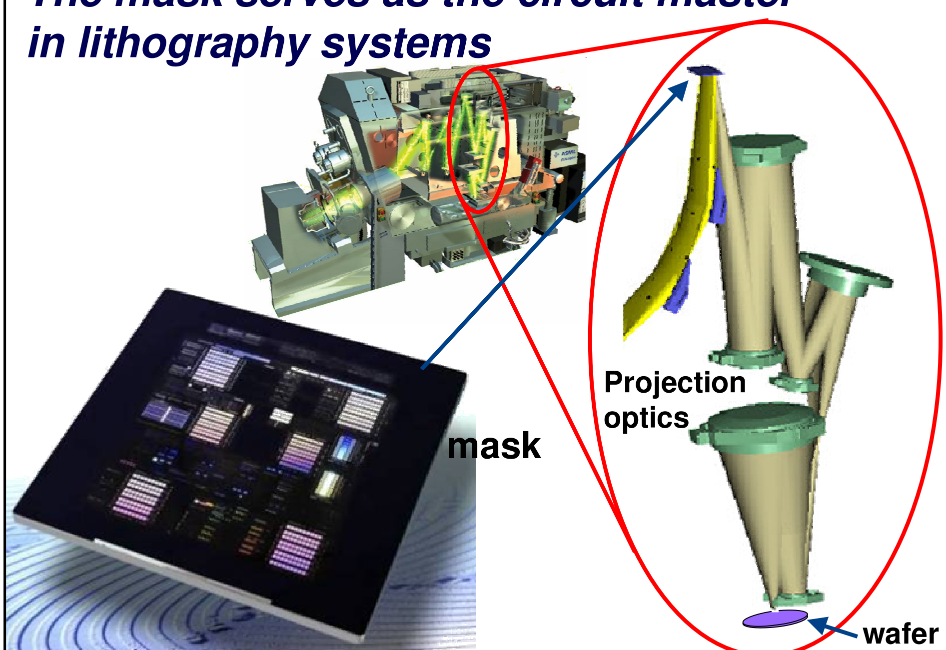


- 35 nm 1:1 contacts on 5x EUV mask
- RMS 1x diameter variation = 1.1 nm
- Resist var. = 4.0 nm

Resist blur dominates MEEF

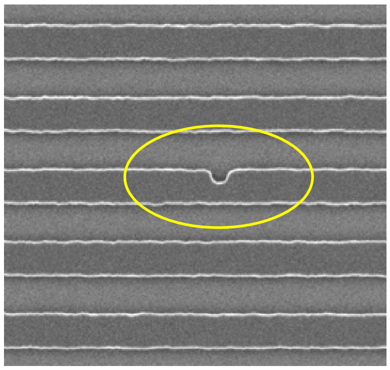


The mask serves as the circuit master in lithography systems

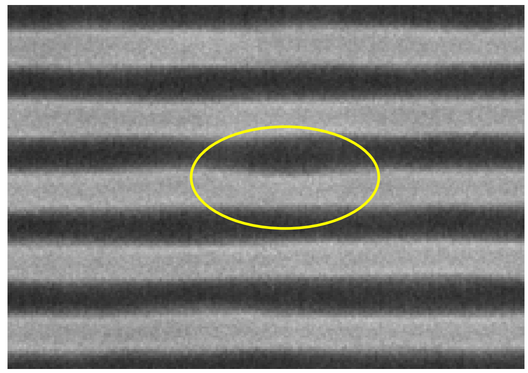


Pattern defects on become replicated problems on the wafer, although attenuated by optic and resist

Mask: 60-nm defect

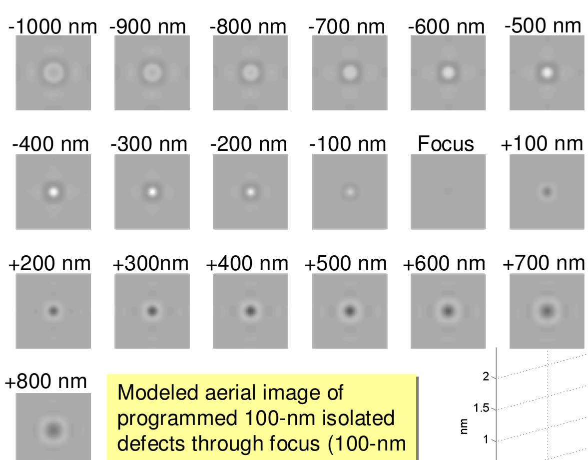


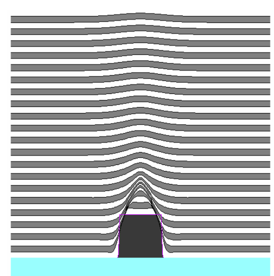
Resist: 9% CD Change



Data courtesy of Ted Liang, Intel
Details published at Photomask Japan, 2006

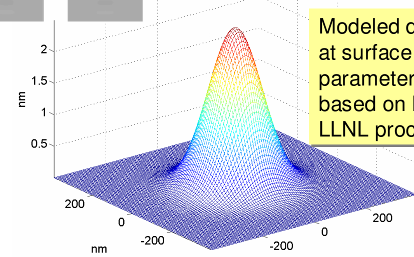
Buried (phase) defects become intensity after band-limited imaging and further enhanced by defocus





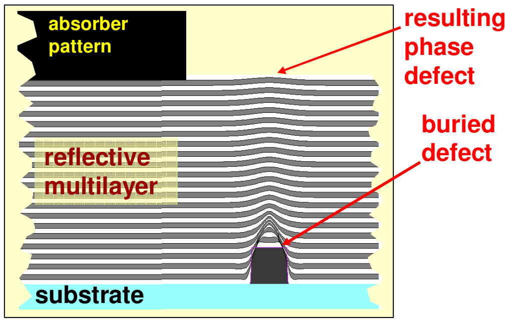
Modeled aerial image of programmed 100-nm isolated defects through focus (100-nm steps)

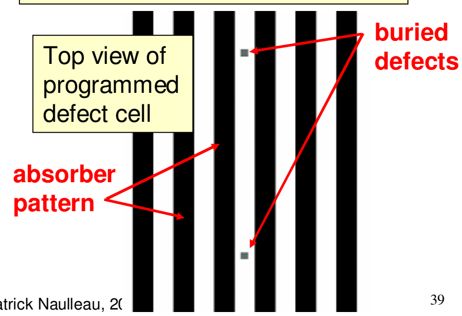
100-nm defects not expected to be printable at Esize)

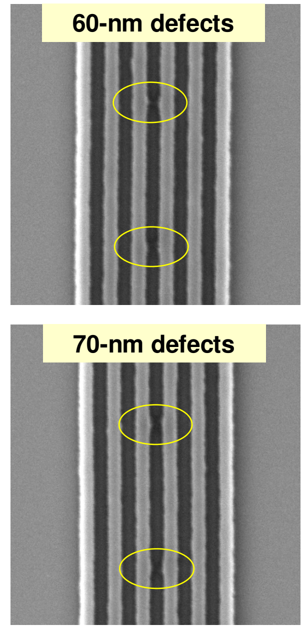


Modeled defect at surface: parameters based on latest LLNL process

Programmed "buried" defects developed to study critical mask issues

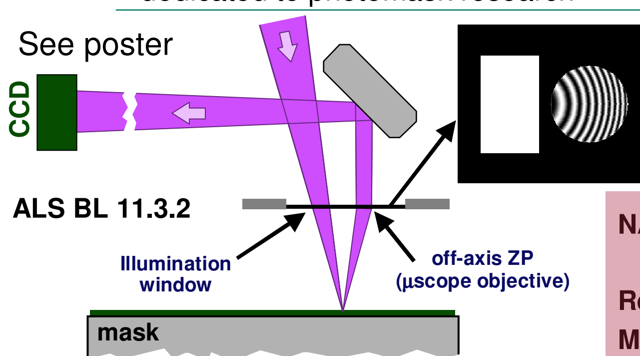






The world's highest-performance EUV microscope
dedicated to photomask research

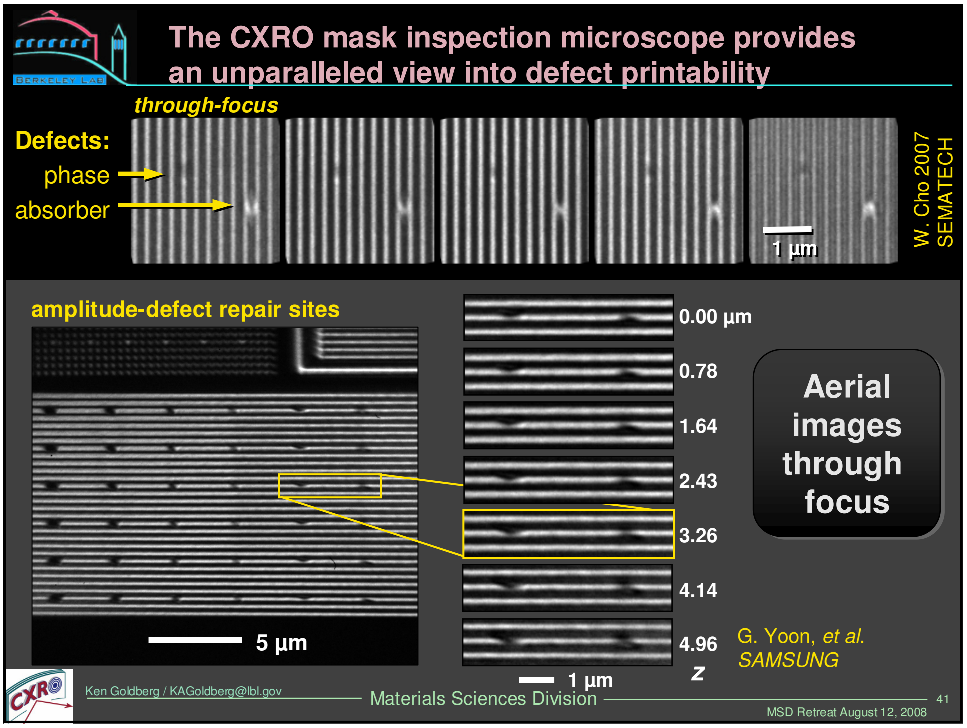
See poster



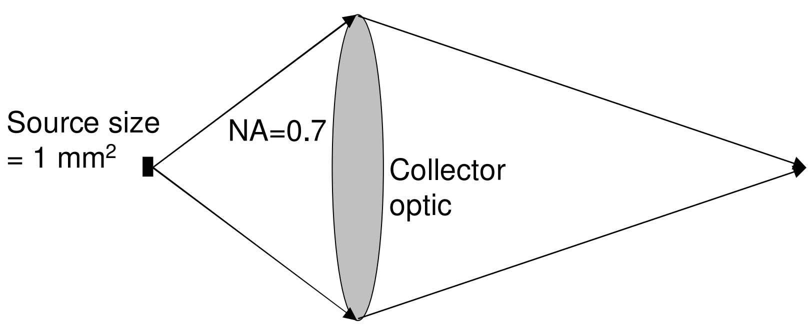
NA = *real-time selectable*
0.25–0.35 (4x)
Res. ≥ 93 nm (23 @ 4x)
Mag = 800–1000x

- **International EUV program's primary tool for at wavelength mask defect inspection and cross correlation with complimentary techniques**
- **Spatial resolution approaching 90 nm at the mask (23 at wafer)**
- **Working with partners regarding future upgrades. Special attention to supporting the development of commercial tools.**

Ken Goldberg / KAGoldberg@lbl.gov



Implications of etendue limits for mask inspection microscopy



- A 1 mm source with 45-degree collection would have an etendue of ~2 mm^2 sr (min σ = 0.53)
- A 0.1 mm source with 70-degree collection would have an etendue of ~0.04 mm^2 sr (min σ = 0.08)

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